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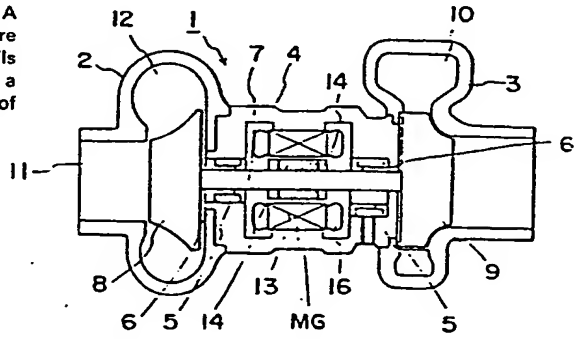
(54) **Turbocharger for internal combustion engines.**

(57) A turbocharger (1) for an internal combustion engine includes a turbine drivable by the exhaust energy of the internal combustion engine, and an air compressor coupled by a shaft (7) to an impeller (9) of the turbine for charging air into engine cylinders in response to rotation of the shaft. A rotor (13) is mounted on the shaft and stator coils are disposed around the rotor. The rotor and the stator coils jointly constitute a motor-generator which operates as a motor or a generator dependent on operating conditions of the internal combustion engine.

Fig. 1



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TURBOCHARGER FOR INTERNAL COMBUSTION ENGINES

The present invention relates to a turbocharger for an internal combustion engine.

The output of an internal combustion engine is produced by combusting a mixture of fuel and air. To increase the engine output, it is necessary to introduce as much air as possible into the engine cylinders.

To meet the above requirement, internal combustion engines of today are equipped with a turbocharger having a turbine driven by the energy of an exhaust gas and an air compressor operatively coupled or integrally joined to the turbine, the air compressor being rotated by the turbine to charge a more-than-normal amount of air into the engine cylinders to burn the fuel efficiently. Therefore, the turbocharged internal combustion engine has an increased charging efficiency to produce a high output and a high torque while simultaneously achieving improved fuel consumption.

However, although the conventional turbochargers can produce a large torque increase in medium and high speeds of rotation of the engine, the exhaust energy which tends to be excessive in high-speed and low-load engine conditions has to be discharged into atmosphere. Under low-speed and high-load engine conditions, no sufficient exhaust energy is obtained, and hence no sufficient air can

be charged into the engine cylinders, with the result that the torque rises only slightly and no large freedom of selection of transmission gears is available. Therefore, the possibility to replace large-size internal combustion engines with small-size turbocharged internal combustion engines is small though there is some improvement in the engine output. Where a small-size internal combustion engine is turbocharged for a greater engine output, it would be advantageous if the engine output could be increased without increasing the number of transmission gears by reducing a final gear ratio or increasing the mechanical strength of each gear. However, since the engine torque is low in low-speed engine rotation, the desired performance for the aubomobiles to climp up slopes could not be achieved unless the transmission were altered to a large extent.

It has been propsoed to assist the turbocharger by a generator in low-speed engine rotation for thereby increasing the air charging efficiency at the low engine speed. With this proposal, however, it is necessary to attach heavy windings, pole pieces, or permanent magnets to the driven component, thus increasing the rotational inertia thereof. As a consequence, the turbocharger will not function sufficiently.

It is an object of the present invention to provide a turbocharger for an internal combustion engine,

which has a motor-generator that can operate as either a motor or a generator dependent on the operating condition of the internal combustion engine.

Another object of the present invention is to provide a turbocharger for an internal combustion engine, which assists the operation of an air compressor when the engine rotates in a low-speed range and converts an excessive energy of the exhaust gas into a recoverable electric power in a medium- and high-speed range of engine rotation.

Still another object of the present invention is to provide a turbocharger for an internal combustion engine, which has a motor-generator that is compact and lightweight.

According to the present invention, there is provided a turbocharger for an internal combustion engine, including a turbine drivable by the exhaust energy of the internal combustion engine, an air compressor coupled by a shaft to an impeller of the turbine for charging air into engine cylinders in response to rotation of the shaft, and a motor-generator composed of a rotor mounted on the shaft and stator coils disposed around the rotor, the motor-generator being operable as a motor or a generator dependent on operating conditions of the internal combustion engine.

The above and other objects, features and advantages of the present invention will become more

apparent from the following description when taken in conjunction with the accompanying drawings in which preferred embodiments of the present invention are shown by way of illustrative example.

Fig. 1 is a longitudinal cross-sectional view of a turbocharger according to the present invention;

Fig. 2 is a schematic diagram showing the relationship between an internal combustion engine equipped with the turbocharger of the invention and a controller;

Fig. 3 is a longitudinal cross-sectional view of a turbocharger according to another embodiment of the present invention;

Fig. 4 is a cross-sectional view of a larger-diameter portion of a shaft of the turbocharger, which serves as a rotor;

Figs. 5a and 5b are diagrams illustrative of the principles of a three-phase synchronous generator;

Figs. 6a and 6b are disgrams illustrative of the principles of a reluctance generator;

Fig. 7 is a circuit diagram of a control circuit for the reluctance generator;

Fig. 8 is an equivalent circuit diagram of the reluctance generator;

Fig. 9 is a vector diagram explanatory of the equivalent circuit of the reluctance generator; and

Figs. 10a and 10b are diagrams showing the

relationship between angular positions of a rotor and a winding axis.

Fig. 1 shows a turbocharger 1 of the invention in longitudinal cross section. The turbocharger 1 includes a compressor housing 2, a turbine housing 3, and a central housing 4. The central housing 4 accommodates in its opposite ends fixed bearings 5 and floating bearings 6 slidably rotatable in the fixed bearings 5, respectively. A shaft 7 is rotatably supported at its opposite ends in the floating bearings 6.

To the ends of the shaft 7, there are attached an air compressor impeller 8 and a turbine impeller 9 which are disposed in the compressor housing 2 and the turbine housing 3, respectively. The tubine impeller 9 is rotated by the energy of an exhaust gas supplied into a scroll 10. The compressor impeller 8 serves to effect pressure conversion, in a diffuser 12, on air introduced from an air inlet, and feed the air into engine cylinders.

A ring-shaped magnetic rotor 13 which is elongate in the axial direction is mounted centrally on the shaft 7. The magnetic rotor 13 is composed of a rare-earth magnet genrating an extremely strong magnetic force. Since the rare-earth megnet is highly small in deflective strength and tensile strength, the end faces thereof are held by disks 14 of a metal of high tensile strength, such as titanium or highly strong aluminum. The magnetic rotor 13

is wound by carbon fibers surrounding the outer periphery thereof. Therefore, the magnetic rotor 13 is rigid and durable against centrifugal forces and vibrations applied thereto.

Stator cores 15 and stator coils 16 are disposed in the central housing 4 around the magnetic rotor 13 in radially confronting relation thereto for inducing an alternatng voltage upon rotation of the magnetic rotor 13. The magnetic rotor 13, the stator cores 15, and the stator coils 16 jointly constitute a motor-generator MG.

Fig. 2 illustrates the relationship between an internal combustion engine 17 equipped with the turbocharger 1 and a controller 22. An exhaust manifold 18 is connected to an exhaust port of the internal combustion engine 17, and the scroll 10 of the turbocharger 1 is couled to the exhaust manifold 18. A fuel injection pump 19 is mounted on the body of the internal combustion engine 17, and is combined with a load sensor 20 for detecting the amount of fuel injected, i.e., the magnitude of the load.

The internal combustion engine 17 has a crankcase on which is mounted a rotation sensor 21 for detecting the rpm of the engine, i.e., the rpm of the crank.

The outputs of the sensors 20, 21 are supplied to the controller 22 for controlling the motor-generator MG to operate as a motor or a generator. When the internal combustion engine 17 rotates at a low speed or is subjected to a large load, the motor-generator MG operates as the

motor to rotate the magnetic rotor 13 and hence the turbine impeller 9 for an increased air charging efficiency. When the internal combustion engine 17 rotates at a high speed or is subjected to a small load in low-speed rotation, the motor-generator MG operates as the generator to supply electric power to external loads while allowing the turbocharger 1 to charge air into the engine cylinders.

Operation of the turbocharger 1 is as follows: When the internal combustion engine 17 is started, a high-temperature, high-pressure exhaust gas discharged from the engine 17 through the exhaust manifold 18 into the scroll 10 rotates the turbine impeller 9. At the same time, the compressor impeller 8 is rotated to supply compressed air through the diffuser 12 into the engine cylinders. The combustion efficiency of the engine is thus improved to achieve an increased torque and output.

When the engine 17 rotates in a low speed range at the time it is started or immediately after it has been started, no sufficient exhaust gas energy is supplied to the turbine impeller 9, and hence the amount of air charged by the compressor impeller 8 is small. As a result, the torque and output are not increased. Such engine operating conditions are detected by the load sensor 20 and the rotation sensor 21, and the controller 19 is responsive to detected signals frmo the load sensor 20 and the rotation sensor 21 for supplying electric power to the motor-generator MG which now operates as the motor.

Therefore, the shaft 7 coupled to the magnetic rotor 13 is provided with a combination of the torque generated by the motor and the torque imposed by the exhaust gas energy on the turbine impeller 9 for thereby rotating the compressor impeller 8 at a high speed and high torque.

Accordingly, the engine even when it rotates in the low-speed range can produce a large torque and output by means of the turbocharger 1 assisted by the motor torque, and can power the automobile to start with sufficient acceleration and to climb up slopes with good performance.

When the speed of rotation of the internal combustion engine 17 is progressively increased to increase the exhaust energy, the turbine impeller 7 and the shaft 7 are caused to rotate at a speed higher than the speed of rotation of the motor-generator MG operating in the motor mode. The motor-generator MG then operates as the generator to induce a voltage in the stator coils 16, which is fed back to the power supply. The regenerated voltage can be utilized for charging the battery, for example. As a consequence, the generator conventionally employed on the automobile may be dispensed with or may be of a smaller capacity, rendered compact in size and reduced in cost.

Since the magnetic rotor 13 is constructed of a rare-earth magnet, the generator can be small in size while producing sufficient power without increasing the

rotational inertia of the turbocharger 1.

With the turbocharger according to the present invention, as described above, the operation of the compressor is assisted by the motor mode of the motor-generator so that the charging pressure in the low-speed range of the internal combustion engine will be increased to increase the low-speed torque to provide high-torque engine characteristics. When the engine is in the high-speed range or low-load range, the motor-generator operates as the generator to produce electric power supplied to various loads.

Figs. 3 through 10 illustrate a turbocharger according to another embodiment of the present invention, the turbocharger having a reluctance motor-generator.

Fig. 3 shows the turbocharger in cross section. The turbocharger includes a compressor housing 101, a turbine housing 102, and a central housing 103, which are coupled together by bolts and nuts, not shown.

A compressor impeller 104 and a tubine impeller 105 are rotatably disposed respectively in the compressor housing 101 and the turbine housing 102 and are interconnected by a shaft 106. The shaft 106 is made of low-carbon steel and has portions held in sliding contact with bearings, the sliding contact portions being hardened by high-frequency heating for wear resistance.

The shaft 106 has a central larger-diameter portion 107 having a certain axial length and cut off in

its diametrically opposite portions to thereby provide a portion 108 of an I-shaped cross section, as shown in Fig. 4. The larger-diameter portion 107 serves as the rotor of a reluctance motor-generator, as described later.

The central housing 103 accommodates in its opposite ends fixed bearings 109 and floating bearings 110 slidably rotatable in the fixed bearings 109, respectively. The shaft 106 is rotatably supported at its opposite ends in the floating bearings 110 .

Lubricant oil passages 111 supply lubricating oil to the sliding surfaces between the fixed bearings 109, the floating bearings 110, and the shaft 106.

Stator cores 113 with stator coils 112 mounted thereon are disposed as a ring form in the central portion of the central housing 103 and are positioned in confronting relation to the outer periphery of the larger-diameter portion 107 in the vicinity of the portion 108 of I-shaped cross section. The stator coils 112 are wound around the stator cores 113 as three-phase motor-generator coils.

The portion 108, the stator coils 113, and the stator coils 112 jointly constitute a reluctance motor-generator MG.

A controller 114 is responsive to the magnitude of the load on the engine and the intake air pressure for operating the reluctance motor-generator MG as a motor for assisting the turbocharger or as a generator for generaing

electric power for use by external loads.

Designated at 115 is a load sensor mounted on an injection pump or the like, 116 an intake air pressure sensor mounted on an intake manifold or the like, and 117 an air/fuel ratio memory for storing appropriate air/fuel ratios for various loads and intake air pressures. The controller 114 computes a suitable air/fuel ratio and supplies a motor driving current to the reluctance motor-generator MG based on the result of computation for assisting the compressor in charging air.

A voltage generated by the motor-generator MG is converted into a DC voltage of a suitable level by a voltage converter 118. The voltage-coverted power charges a battery 119.

When the internal combustion engine rotates at a low speed and high load as when the automobile starts running or climbs up a slope, the controller 114 is responsive to the output signals from the load sensor 115 and the intake air pressure sensor 116 for supplying a motor driving current to the stator coils 112 of the reluctance motor-generator MG.

The reluctance motor-generator MG now operates as a motor to assist the rotation of the shaft 106 having the larger-diameter portion 107 serving as the rotor, so that the amount of air charged by the compressor impeller 105 into the engine cylinders can be increased. Therefore, the air/fuel ratio is increased to enable the air-fuel mixture

to be ignited for powerful expolosion, resulting in an increased output and torque.

When the internal combustion engine rotates in medium- and high- speed ranges, the turbine impeller 105 rotates at high speeds and the compressor impeller 104 charges a sufficient amount of air into the engine cylinders. At the same time, the larger-dimeter portion 107 is driven as a generator rotor to induce a voltage across the stator coils 112, and the induced voltage is converted by the voltage converter 118 for charging the battery 119 or feeding loads, not shown.

The principles of operation of the reluctance motor-generator MG as the generator will be described.

Figs. 5a and 5b show the principles of a three-phase synchronous generator and the waveshape of an electromotive force induced. An I-shaped rotor M composed of a permanent magnet is rotatable in phase coils A_1 - A_2, B_1 - B_2, and C_1 - C_2. When the rotor M is in the illustrated position, electromotive forces induced in the coils are directed as shown in Fig. 5a, and at this time the electromotive force ea in the coil A_1 - A_2 is maximum.

When a load is put on the generator and an armature current ia_1 flows in phase with the electromotive force ea, the current in an armature winding coincides with the electromotive force distribution shown in Fig. 5b at $\theta = 0$ since the current and voltage in each phase are held in phase with each other. The armature current generates

a magnetomotive force across the gap in the direction of the arrow P in Fig. 5a.

Thus, if the electromotive force ea and the armature current ia_1 are in phase with each other, then the magnetomotive force is generated by the armature current and lags a magnetic flux produced by the field coils by a phase angle of 90^o.

Therefore, when currents ia_2, ib_2, ic_2 (Fig. 6b) are passed which lead the no-load induced electromotive force ea by 90^o, the current ia_2 leading the electromotive force ea by 90^o flows through the coil $A_1 - A_2$, and the magnetomotove force due to the current ia_2 falls to zero at $\theta = 0$. However, a magnetomotive force is generated by the currents ib_2, ic_2 in the direction of the arrow Q (Fig. 6a) which is the same direction as that of the field flux, thereby increasing the field flux.

As a result, the process of generating currents leading the no-load induced electromotive force by 90^o at all times and continuously changing the magnitudes of the currents is equivalent to an ordinary process of regulating the field current in the synchronous generator, as shown in Fig. 6a. It follows that a generator having the same function as the synchronous generator can be achieved without field coils and a permanent magnet. Such a generator has a reduced power factor as both load and field currents have to be passed through the armature coils.

Fig. 7 shows a control circuit for the reluctance

generator. Designated at 121 are armature coils of the generator, 122 a rotor, 123 a load, 124 a source of leading-phase reactive power, and 125 a rotor position sensor for detecting the angular position of the rotor 122 at all times and enabling the source 124 to supply excitation currents to the armature coils 121. When the rotor 122 is rotated, electromotive forces are induced in the armature coils 121 to supply electric power to the load 123.

As is apparent from the above principles of operation, the reluctance generator is the same as an ordinary salient-pole synchronous generator from which the field winding has been removed. The reluctance generator has an equivalent circuit as shown in Fig. 8 in which an electromotive force E_0 generated by a main flux due to the field winding in the salient-pole generator is zero.

Now, an analysis will be made to determine how the generator output is affected by Xq, Xd where the counterelectromotive force generated by connection to the load 3 is indicated by Va. For simplifying the analysis of operation of the generator, winding resistances Rq, Rd are neglected, and an quadrature-axis impedance Zq is regarded as being equal to jXq while a direct-axis impedance Zd is regarded as being equal to jXd. The vector diagram as shown in Fig. 5 is then plotted.

In Fig. 5,

$$Ia \cdot \cos\theta = Iq \qquad \ldots(1)$$

$$Ia \cdot \sin\theta = Id \quad \ldots(2)$$

$$Va \cdot \cos\delta = Xd \cdot Id \quad \ldots(3)$$

$$Va \cdot \sin\delta = Xq \cdot Iq \quad \ldots(4)$$

One-phase output Pph is given by:

$$Pph = Va \cdot Ia \cdot \cos\psi$$

$$= Va \cdot Ia \cdot \cos(\theta + \delta) \quad \ldots(5)$$

By modifying the equation (5),

$$Pph = 1/2\ (1 - \alpha) Xd \cdot Ia^2 \sin 2\theta \quad \ldots(6)$$

With $\alpha = Xq/Xd$ and by modifying the equation (6) based on the equations (1) through (4),

$$Va = Xd \cdot Ia \sqrt{\sin^2\theta + \alpha^2 \cos^2\theta} \quad \ldots(7)$$

The one-phase output Pph then becomes:

$$P_{ph} = \frac{(1 - \alpha) \sin^2\theta}{2\sqrt{\sin^2\theta + \alpha^2 \cos^2\theta}} Va \cdot Ia = K_1 Va \cdot Ia \quad \ldots(8)$$

In order to increase the output Pph, Xd should be increased to as large an extent as possible and Xq should be reduced to as small an extent as possible since Ia is an allowable current for the coils and can be suppressed, in view of the equation (6).

Thus, when the angular position of the rotor coincides with the direction of the coil axis as shown in Fig. 10a, then the magnetic flux generated by the coil passes in the direction of the solid-line arrow R, so that the magnetic path has a small magnetic reluctance and the coil has an increased self-inductance L_1. When the angular position of the rotor is normal to the coil axis as illustrated in Fig. 10b, then the magnetic path has a large

magnetic reluctance and the coil has a reduced inductance L_2. Therefore,

$$Xd = 3/2 \cdot \omega L_1 \quad \ldots(9)$$

$$Xq = 3/2 \cdot \omega L_2 \quad \ldots(10)$$

As is apparent from the above principles, the portion 108 of I-shaped cross section of the larger-diameter portion 107 of the shaft 106 and the stator coils 112, as shown in Figs. 3 and 4 constitute the rotor of the reluctance generator. The rotor with a smaler magnetic reluctance in the direction of a d-axis and a larger magnetic reluctance in the direction of a q-axis in the portion 108 can reduce the value α and increase the output Pph.

The reluctance generator can be used as a motor with the larger-diameter portion acting as a rotor by applying voltages to the stator coils 112. The present invention is concerned with a turbocharger having a reluctance motor-generator utilizing such motor-generator characteristics.

With the present invention, as described above, the motor-generator driven by the exhaust-driven turbine operates as a motor to assist the turbine in its rotation when the internal combustion engine rotates in the low-speed range, thus providing a sufficient air charging capability for increasing an engine output and torque.

When the internal combustion engine rotates in the medium- and high-speed ranges or in the low-speed

high-load range, the motor-generator operates as a generator for generating electric power to provide a power supply for energizing lamps and illuminating indicators, and actuating meters, horns, window wipers, heaters, and ignition.

The reluctance motor-generator has the shaft connecting the compressor impeller and the turbine impeller and used as the rotor. The shaft is highly suitable for use as the rotor which can withstand high-speed rotation without the danger of getting separated, broken, or vibrated under centrifugal forces applied.

Inasmuch as the diameter of the rotor can be minimized, the turbocharger with the generator can be reduced in size.

Since the reluctance motor-generator employs no field coil and no permanent magnet, the reluctance motor-generator is simple in construction, low in cost, and light in weight.

As no electric power is supplied to or received from the rotor, no brush is employed, and hence the rotor is suitable for high-speed rotation.

Although certain preferred embodiments have been shown and described, it should be understood that many changes and modifications may be made therein without departing from the scope of the appended claims.

CLAIMS :

1. A turbocharger for an internal combustion engine having engine cylinders, comprising:

a turbine drivable by the exhaust energy of the internal combustion engine and having an impeller;

an air compressor coupled by a shaft to said impeller for charging air into the engine cylinders in response to rotation of said shaft;

a motor-generator composed of a rotor mounted on said shaft and stator coils disposed around said rotor; and

control means for operating said motor-generator as a motor or a generator dependent on operating conditions of the internal combustion engine.

2. A turbocharger according to claim 1, wherein said motor-generator is driven as the motor when the internal combustion engine operates in at least a low-speed high-load range.

3. A turbocharger according to claim 1, wherein said motor-generator is driven as the generator when the internal combustion engine operates in a high-speed range.

4. A turbocharger according to claim 1, wherein said motor-generator is driven as the generator when the internal combustion engine operates in a low-load range.

5. A turbocharger according to claim 1, wherein said rotor comprises an axially elongate ring-shaped rare-earth magnet.

6. A turbocharger according to claim 5, including

disks of a metal of high tensile strength, said magnet being held at its opposite ends by said disks, respectively.

7. A turbocharger according to claim 5, including carbon fibers wound around the outer periphery of said magnet.

8. A turbocharger according to claim 1, wherein said rotor is constructed as a portion of said shaft and has a magnetic reluctance in a first direction normal to an axis of said shaft, smaller than a magnetic reluctance in a second direction normal to the first direction and to the axis of said shaft, said rotor having a substantially I-shaped cross section.

9. A turbocharger according to claim 8, wherein when said motor-generator operates as the generator, said stator coils are supplied with armature currents leading a no-load induced electromotive force by 90^{o}.

Please amend the specification of the application papers as follows.

1. Fig. 5 in page 14, line 25 and 26 to be amended to Fig. 9.

2. The compressor impeller 105 in page 11, line 25 be amended to compressor impeller 104.

The request for correction is allowed under R. 88 EPC / with the exception of the deleted points /.
THE HAGUE,
RECEIVING SECTION 12 JUIL. 1985

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Fig. 1

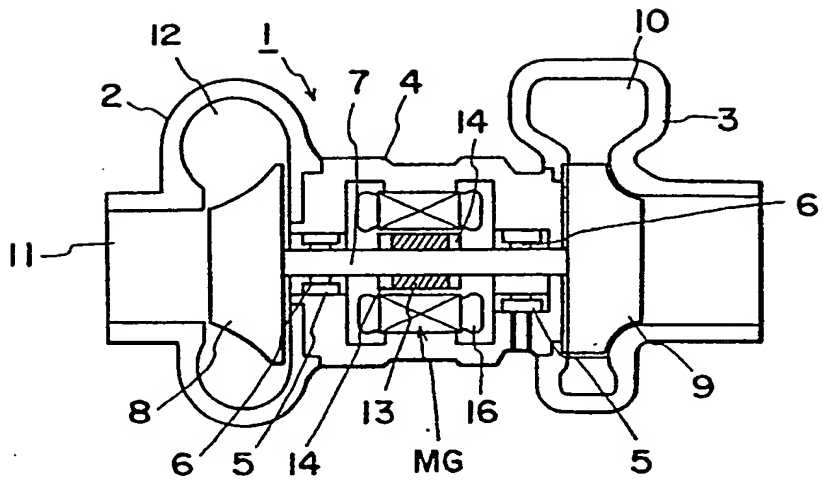

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Fig. 2

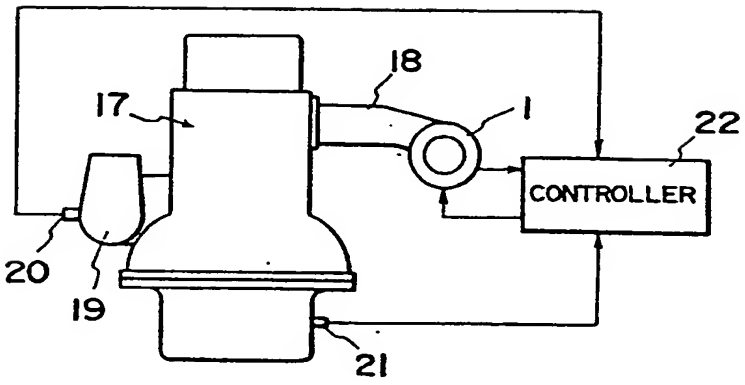

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Fig. 3

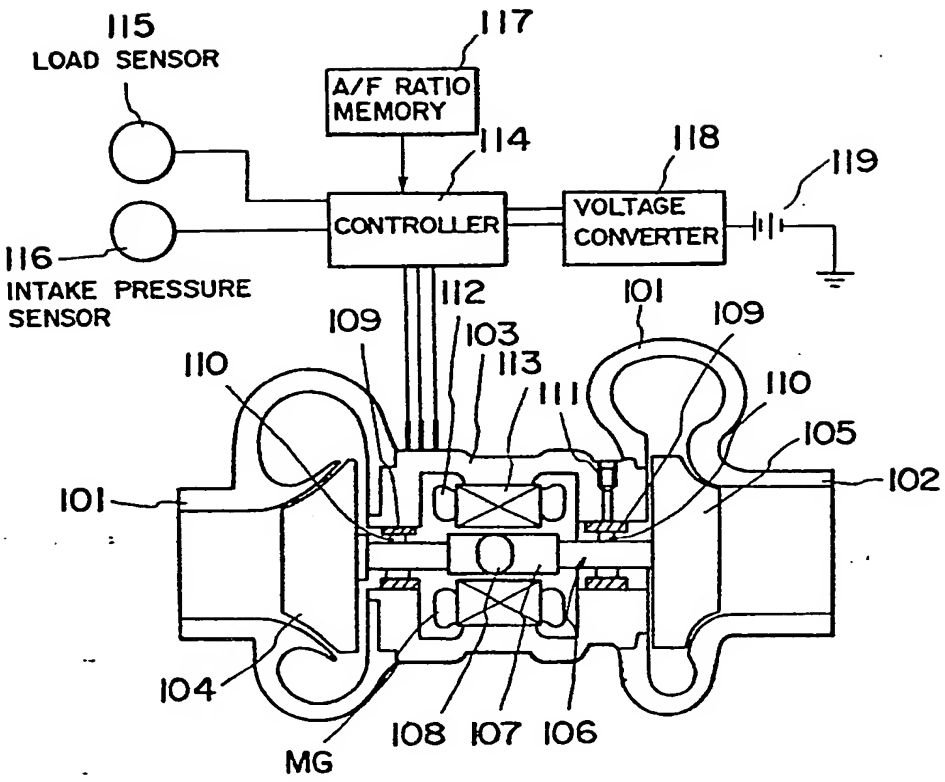

Fig. 4

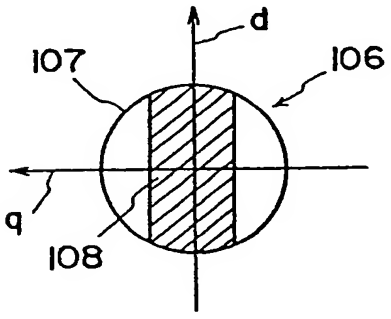

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Fig. 5a

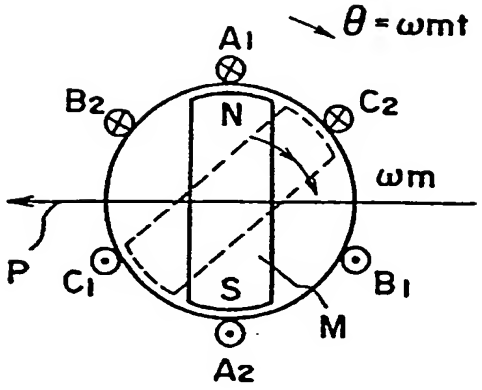

Fig. 5b

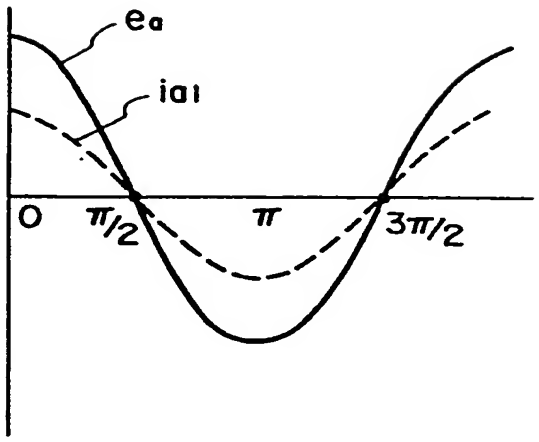

Fig. 6a

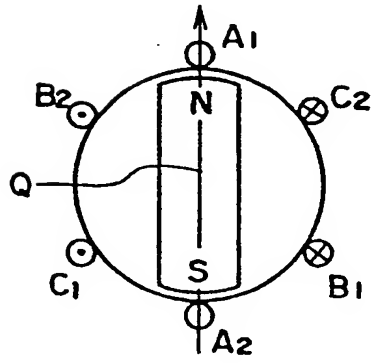

Fig. 6b

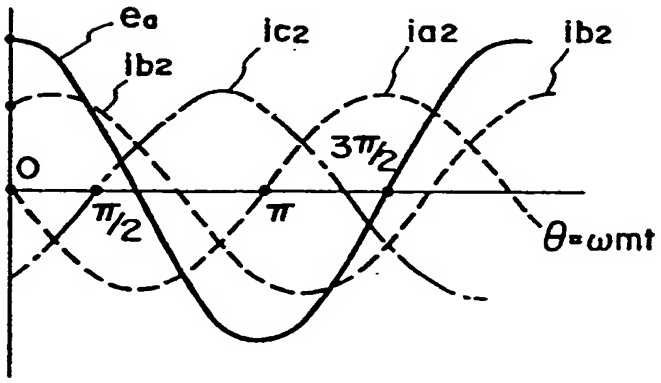

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Fig. 7

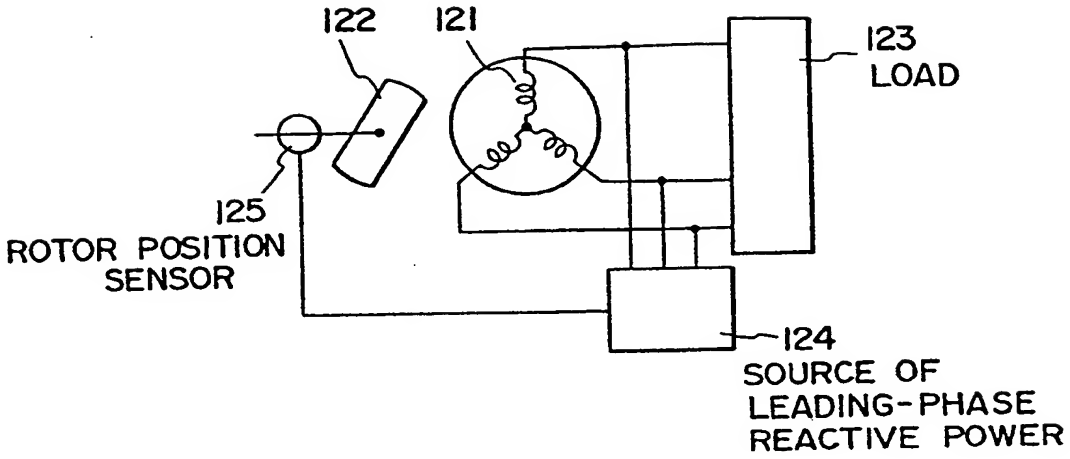

Fig. 8

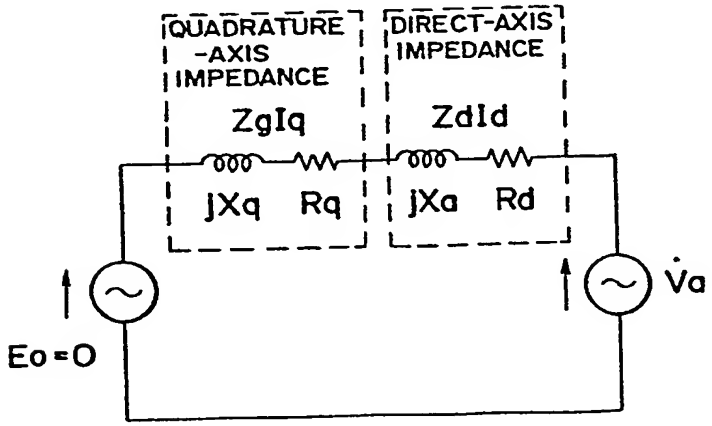

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Fig. 9

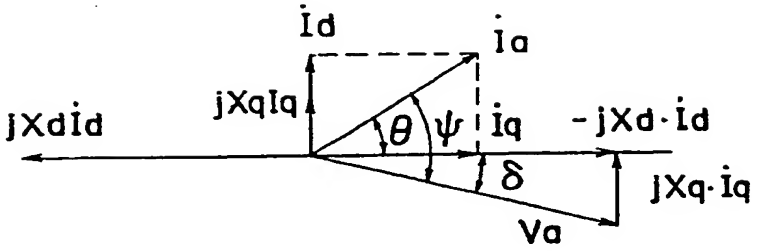


Fig. 10a

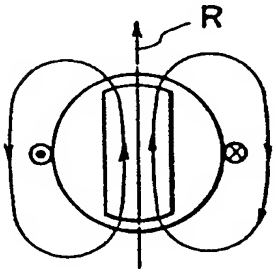
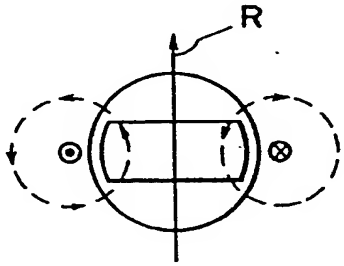


Fig. 10b



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Application number

EP 85 30 1843

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
X	DE-A-2 206 450 (DAIMLER- BENZ) * Page 2, paragraph 3 - page 6, line 4; figures 1-3 *	1-3	F 02 B 37/10 F 02 B 39/10
X	FR-A-2 183 337 (BRETING) * Page 2, line 20 - page 4, line 30; figures 1,2 *	1,2	
X	DE-A-2 808 147 (BRETSCHNEIDER) * Page 4, paragraph 3 - page 7, paragraph 1; figures *	1	
X	EP-A-0 079 100 (MICROTURBO) * Page 2, line 37 - page 6, line 8; figure 1 *	1	
X	DE-A-2 951 136 (BEHNERT) * Page 4, line 2 - page 5, line 8; figures *	1	TECHNICAL FIELDS SEARCHED (Int. Cl.4)
A	US-A-4 067 101 (YOSHIKAZU) * Column 2, lines 49-59; figures 1,2 *	5,6	F 02 B H 02 K
A	GB-A-2 117 188 (K.K. OKUMA) * Page 1, lines 104-108, figures *	7	

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	26-06-1985	HAKHVERDI M.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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EUROPEAN SEARCH REPORT

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
A	FR-A-2 072 611 (ERNEST) * Page 2, line 24 - page 3, line 3; figures 1,2 *	8	

TECHNICAL FIELDS SEARCHED (Int. Cl.4)

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THE HAGUE	26-06-1985	HAKHVERDI M.

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